Assessment of the Cycle-to-Cycle Noise Level of the Geosat Follow-On, TOPEX, and Poseidon Altimeters

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ABSTRACT

The Geodetic Satellite (Geosat) Follow-On (GFO), Ocean Topography Experiment (TOPEX), and Poseidon altimeter white-noise levels have been evaluated using a technique based on high-pass filtering of 1-Hz sea surface height time series. High-pass filtering removes the geoid and oceanography signals while revealing the random noise. This filtering technique is simpler to use than the repeat-track method, gives essentially the same results, and makes it easier to analyze much larger amounts of data to investigate subtle variations in noise levels. The new noise-level measurements provided here all show stable noise-process characteristics from cycle to cycle, with a linear dependence of the noise level upon significant wave height (SWH). The GFO altimeter noise level is estimated to be 2.5 cm for an SWH of 2 m. The Poseidon noise level is estimated at 2.0 cm for the same value of 2 m SWH. The TOPEX altimeter noise level is 1.8 cm when the dual-frequency ionospheric correction is included; when this noisy correction is not used, the level is reduced to 1.5 cm. Although the dual-frequency ionospheric correction provides an average improvement over the ''Doppler orbitography and radiopositioning integrated by satellite'' (DORIS) correction, high-frequency noise enters into the dual-frequency correction via noise from the Ku- and C-band ranges. Because the variations in ionospheric refraction are a relatively long wavelength global effect (with strong dependence on latitude), the dual-frequency ionospheric correction should be low-pass filtered before use, and this correction should not be included when estimating the high-frequency noise level of the altimeter.

1. Introduction

The Geodetic Satellite (Geosat) Follow-On (GFO) and the Ocean Topography Experiment (TOPEX)/Poseidon (T/P) missions are dedicated to the observation of the ocean surface topography from orbit using satellite-based nadir-pointing radar altimeters. The basic data are altimeter-derived sea surface heights (SSH) that are obtained by taking the difference of the satellite altitude (relative to a reference ellipsoid) as determined by precision orbit tracking and the altimeter range as determined by precise measurement of the round-trip time of flight of the radar signal. The range estimate requires environmental corrections, for example, for atmospheric propagation delays and sea-state biases. Measurements of the range in 1-s averages are generally analyzed in applications of altimeter data.

An integral part of the analysis of altimeter datasets is a quantitative evaluation of altimeter instrument noise. This is necessary for monitoring improvements in measurement systems, for projecting future capabilities, and for properly analyzing the data in oceanographic and geodetic applications. The precision of satellite radar altimeter instruments has improved since the earlier programs [the *Geodynamics Experimental Ocean Satellite* (*GEOS-3*), Seasat, and Geosat], and continuous improvements in environmental corrections (orbits, ionospheric refraction, tides, etc.) have resulted in modern altimeters (e.g., TOPEX) having absolute errors of only a few centimeters.

The largest contributions to the measured sea surface topography come from 1) geoid undulations, 2) dynamic oceanography associated with geostrophic surface currents and eddies, 3) tides, 4) the sea surface response to atmospheric pressure loading, and 5) altimeter instrument noise; not included in this list are orbit errors, which are very long in wavelength and relatively small in amplitude and which may be ignored for the purpose of this discussion. The elevation variability of the geoid signal is on the order of meters to tens of meters; the oceanographic signals are from a few centimeters to no more than 2 m; and tides in the open ocean are generally less than 1 m but can be predicted by numerical models to better than a few centimeters. The atmospheric loading or ''inverse barometer'' effect is a few centimeters, and the instrument noise is also at the few-centimeter level. One additional, but small, effect comes from ocean waves and swell. Although very obvious to mariners, waves are not a major factor in the measured sea surface topography, because each altimeter pulse illuminates a circular area on the ocean that is several kilometers in diameter, so the local waves are approximately averaged out. Actually, the averaging out is not perfect, and there is an ''electromagnetic bias'' correction proportional to significant wave height (SWH) and wind speed that should be made for the most precise uses of altimeter data (e.g., Gaspar et al. 1994).

The original analyses of satellite altimeter noise were developed in the context of geodesy, and ''noise'' was defined as any effect in the data other than the geoid signal. Noise was studied by comparing the repeatability of the data observed along colinear or repeat tracks. By differencing the data series along two repeat tracks (having a cross-track offset of no more than 1 km), the time-invariant geoid signal cancels out and a time series of random noise remains. Spectral analysis of the difference time series reveals two main components of the noise: 1) a ''colored'' noise process behaving approximately like a first-order Markov random process (this is attributable to oceanography) and 2) a lower-powered additive contribution that appears as a ''white-noise floor,'' visible as the noise spectra flatten out at high frequency (Brammer and Sailor 1980; LeSchack and Sailor 1988). The white-noise component was attributed to electronic noise in the altimeter instrument, and, indeed, the on-orbit results are generally consistent with laboratory measurements of instrument noise made before launch.

However, as this paper shows, a portion of the white-noise component can be attributed to random scattering effects from ocean waves, since the white-noise level is found to be proportional to the SWH. The repeat-track method of studying noise in altimeter data requires that repeat tracks be matched up and aligned, that environmental corrections (e.g., tides) be applied independently to each track, and that power spectra be computed from the difference segments. This is straightforward but was not easily automated to process large amounts of data. Consequently, the early studies did not apply this method to very many repeat-track pairs and did not investigate in much detail the variability in noise that might occur as a function of aging of the spacecraft or that might be due to environmental factors such as SWH. Nevertheless, the white-noise level for each altimeter was found to be fairly consistent, and the average values obtained for different altimeters are a good measure of the relative quality of those instruments. For example, *GEOS-3,* launched in 1975, had a white-noise level of about 23 cm. For Seasat in 1978 the result is 5 cm, and for Geosat in 1985 it was 3 cm (Sailor and LeSchack 1987; Sailor and Driscoll 1992). Le Traon et al. (1994) analyzed TOPEX and Poseidon spectra and estimated that the Poseidon repeat-track noise level is about 3 cm and the TOPEX repeat-track noise level is about 1.8 cm, calculated as rms. All of these numbers have been determined without consideration of the SWH. They all represent the integrated white-noise power in the frequency band from -0.5 to $+0.5$ Hz (the folding frequencies for data sampled at 1 Hz), so these noise values correspond to a 1-s average. Sailor (1993) defines the signal processing and spectral analysis techniques in detail and gives examples that confirm the validity of the noise-modeling approach that involves repeat tracks.

To summarize and conclude, the assessment of the altimeter noise by high-pass filtering 1-Hz sea surface height time series can be applied to single-frequency altimeter data such as from GFO and the French altimeter Poseidon, as well as to dual-frequency altimeter data such as from TOPEX. As pointed out in an early analysis (Driscoll and Sailor 2001), this approach to estimating the altimeter noise provides results similar to those derived from the noise spectra computed from differenced repeating ground tracks and is also in agreement with the alternate operational TOPEX Ku-band range noise estimation method as presented in this paper

This paper presents the first application of the high-pass-filtering method to multiple altimeters for determining the noise level in satellite altimeter data. This technique is found to be valuable because it allows the noise levels to be determined from individual tracks rather than from repeat tracks, facilitating time-dependent noise-level monitoring. The most obvious effect on the observed noise level is SWH, and, for all altimeters, the noise level increases linearly with increasing SWH. Other than the dependence on SWH, the noise level is very stable from cycle to cycle for GFO, TOPEX, and Poseidon. Thus, the high-pass-filtering technique will be useful for monitoring the performance of any altimeter as the satellite ages and for comparing the relative performance of different altimeters with respect to high-frequency noise.

As shown here, the effective number of independent radar return pulses directly affects altimeter range estimation precision. The new Poseidon-2 altimeters aboard the *Jason-1* satellite transmit at rates of 1800 and 300 Hz, for Ku and C band, respectively. Altimeters aboard *Envisat* operate at 1800 Hz at Ku band and 450 Hz at S band. These rates will thus set limits for both sensor's performance, as pointed out by Quartly et al. (2001).